ENHANCING GRADE CHANGES USING DYNAMIC SIMULATION

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ABSTRACT

A dynamic simulation model of a 3-ply paperboard production process was developed. The simulation model consists of stock preparation and proportioning, short circulations, wire and press sections, and 75 drying cylinders including the steam and condensate system. Functionality of the automatic grade change program used on the machine was modeled as well. Physical, first principles models were used whenever possible. Simulator was extensively validated using historical data. The simulator has been used as a test bench in order to find better values for automatic grade change parameters. First set of the new simulator tested parameters has been carried out to the real machine with good results.

INTRODUCTION

It is common that paper and board machines produce tens of grades to meet different customer specific needs. To avoid large storage, mills have to change grades frequently. Grade changes (GC) have a large impact on the machine production efficiency, so it is relevant to make all possible efforts to minimize the production losses they cause. Careful production planning does a lot. Some paper machines may even get rid of the losses with a production cycle where basis weight changes are so small that acceptance limits of the grades overlap. However, the minimum basis weight change between grades may be 20 g/m^2, there are simultaneous changes to fiber furnish type, filler content and type, color, and so on. This kind of issues keep the GC of paper and board machines as a very interesting and challenging research topic.

In literature grade change has been a popular subject and many times dynamic simulation has had a major role in those studies. Already in 1988, Miyanishi et al. [1] demonstrated effects of machine chest volume, first pass retention, and dry broke ratio in GC. They also showed the effect of increasing filler loading in the initial period of the GC in which filler type is changed.

Historically GC's have been accomplished manually by machine operators and many of the studies deal with the question how to automate the operations needed. The basic idea of automatic grade change (AGC) is simple: ramping of manipulated variables with preplanned targets and mutual coordination. However, it is challenging to tune the system to give good performance simultaneously for all quality variables, and many approaches have been presented to overcome this problem. Ihalainen and Ritala presented an idea to numerically optimize the actions in GC's by using dynamic simulation [2]. Murphy et al. proposed a dynamic coordinator to reduce the basis weight and moisture content upsets during GC's [3,4]. Thick stock flow was used as a coordinating actuator. Other than linear control curve pattern was used by Mori et al. too [5]. Additionally, Mori et al. presented a new iron plate drying model that enables fast calculation of steady state moisture and temperature profiles for the drying section. They told, that the model is tuned before each GC using on-line measurements, and after the tuning the model is able to accurately predict steam pressures for the new grade. For a successful GC it is very important that new grade's target values are reasonably good, and the most difficult to predict are steam pressures. Besides Mori et al., many other papers concern the different estimation methods [4,6,7].

The traditional AGC methods switch the machine's quality controls off when performing grade changes. Also approaches to do GC's under feedback control have been presented. Välisuo et al. suggested use of model predictive control with non-linear models [8]. Recently, Kuusisto et al. have discussed the same subject [9]. They emphasize the importance of moisture dynamics in the use of multivariable predictive control in AGC. The moisture model must handle the complicated dynamics due to the changing machine speed, paper basis weight and ash content, but still be easily commissioned. A totally different approach in speeding-up GC's has been presented in papers that introduce new papermaking concepts with considerably faster transient dynamics than before [10].

In this paper, we present our experiences in using dynamic simulation to improve GC's in a Finnish multi-grade, multi-ply board machine. Our approach has not been to develop a new algorithm or a control strategy, but to enhance the operation of the mill's present AGC system. The structure of the simulation model and the main calculation principles are described. Simulation results are shown and discussed. Finally, the way to use the simulator at the mill is presented before looking to the future work.

PROBLEM FORMULATION

The board machine in question produces liquid packaging boards having basis weight area of 170-350 g/m^2. The machine has three fourdrinier wires, one of which is equipped with a top wire unit. There are three press nips in the press section. Five two-tier dryer groups with conventional steam-heated cylinders are used to dry the base board to about 3% moisture prior to a size press. The following two steam groups before the on-line coating have still been included into the simulation model. The machine speed varies between 200 and 450 m/min.

An average of one GC per day is done on the machine. For many years, a specific automatic grade change program has assisted operators at the mill. The control variables that are included in the AGC are:

- wire speed
- thick stock flows for 3 layers
- slice opening of the 3 headboxes
- jet-wire ratios for 3 headboxes
- steam pressures in steam groups 5 and 7

The AGC program calculates targets for the thick stock flows and the two steam pressures. Pressures in other steam groups are following the pressures in the 5th and 7th group with given ratios. The AGC also suggests typical grade operating values for the wire speed, slice openings and jet-wire ratios, and the operator may change them if necessary. After GC has been initiated, the AGC coordinates the mutual delays and handles ramping of the variables. This coordination is pre-planned by giving a start delay, maximum stepping rate and a stop delay for each variable in the GC. Additionally, there is a selection if to synchronize or not the ramping of each variable with the others.

Operators select which of the variables are controlled automatically by the AGC. Usually they let the automatics handle all other variables but the slice openings, which they most often adjust manually. All operators use the AGC and consider it as a useful tool. On the other hand, the general feeling has been that the operation could be improved to give shorter GC times and to reduce moisture fluctuations during the GC's. The AGC's steam pressure prediction for the new grade has been at a satisfactory level, so no attention was paid on that part of the AGC in this study.

Rather big unwanted excursions in the web moisture content have been one of the main concerns in GC's on the machine. Clearly the moisture bounds up or down when the machine speed starts to change and again just after reaching the target speed. The headbox dynamics during the speed change has been nominated as the dominant reason for this kind of moisture disturbance [3,4]. When browsing GC's in historical data it can be seen that this occurs in most of the GC's, but the amplitude of the disturbance varies from case to case. An intuitive reaction is that by better timing the phenomenon could be removed. However, it is very challenging to try to figure out the right actions needed to fix such a fluctuation using just a mind model. In a multi-ply machine like this the number of tuning parameters of the AGC is remarkable. Different ideas compete and conflict. This kind of "opinion engineering" is quite a fragile base to start experiments with the real machine. The simulator was seen as a possibility to play with different ideas before anything is done on the machine.

MODELING

The process model covers the board making process from pulp chests to the end of the base board drying. The model was built using the APROS platform [11]. It is a general-purpose modeling and dynamic simulation tool. The extension of the platform on pulp and paper mill applications is called APMS.

Simulation models are built based on the P&ID's and equipment functional descriptions. High fidelity is achieved by using first principles of physics to describe process operation whenever possible. Conservation of mass, energy and momentum is used in solving pressures, flows, and temperatures in piping networks. Validated and tested model algorithms for process equipment, instrumentation and automation are integrated under the executive control of an advanced graphic user interface. The user builds graphically a model that looks analogous to the corresponding flowsheet in the P&ID's. The simulation model is configured while the flowsheet is being drawn and parameterized. The model structure can be changed any time and the model can be expanded without need to recompile or link the program.

Most of the parameters needed were derived from P&ID's, like pipe diameters, tank volumes, nominal flows, and heads for pumps. Pipe lengths were calculated from piping drawings and some of them were ocular estimates. Equipment elevations from a certain reference level were obtained from layout drawings. Some of the parameters needed a look at construction drawings (like cylinder diameter and shell thickness, or number and dimensions of pipes inside a condensator) or were got from measurement data (like pressure drops in pressure screens). Also, general engineering knowledge is useful in cases when specific information of a piece of equipment is not easily available (like in our case pressure drops in the valves and pipes, and trim types of the control valves).

Mass Preparation and Short Circulation

Refining, mass proportioning and the short circulation of each layer form a large thermohydraulic pressure/flow network which is modeled by connecting model objects for pipes, pumps, valves and tanks etc. together. The incoming stocks to the chests before refining form the starting point for the model. Three fiber components, filler and water are carried along in the system. Ideal mixing was assumed in tanks, but wire pits were divided into several ideally mixed volumes. Refiners, pressure screens and centrifugal cleaners take also part in the pressure/flow network. Screens were defined to have constant separating ratios. Refining is not changing pulp properties in the model, though this feature would further broaden the scope to cases where refining is changed noticeably for the new grade. It would, however, require lot of experiments to capture the effects of refining quantitatively on e.g. water removing in the wire, wet press and drying sections, so we decided to take the first step without modeling any refining effects.

Headbox is the last part of the pressure/flow network before the web model starts. Only the jet-wire ratio controls directly controlling the speed of each head box feed pump were needed of head box controls to get the dynamics correspond very well with measurements. Machine cross direction was neglected in this model. In the machine direction the web is described with the user defined number of elements moving with the machine speed. The web properties that are calculated are moisture content, temperature, basis weight, composition and thickness.

Wire and Press Section

In the wire section model, webs from three separate wires are interconnected into a single one and the compositions of the layers are averaged. We have used constant values for retention of various fiber components and still obtained very good correspondence to measured values, e.g. headbox consistencies. This is due to the relatively high grammage of all produced grades. Filler plays a minor role because its content is very low in all grades. So, no extra effort was taken to explain retention changes in this phase.

Dewatering on the wire part was modeled in a straightforward way, as well. First approach was to use constant dewatering ratio in all wire model components. As an example, it means that the dry solids content of the web and total mass flow to the press section change when e.g. consistency in a headbox changes. Another approach was to use constant dry solids content of the outgoing web in the last part of the wire. Then a change in a head box consistency does not change the dry solids content but the total flow into the press section is still free to change. This approach seemed to work well. Maybe because the operators control the dry line position with slice opening thus keeping the dry solids content in a certain range. If the effect of the slice opening on the dry solids content is not known accurately, it may be better to keep the dry solids content as constant. It is worth mentioning here, that in this study the slice openings, before and after each simulated GC, could be taken from the corresponding historical data.

The decreasing permeability model [12] was used to describe water removal in each of the three press nips:

$$\frac{z}{z_0} = \left(1 + \frac{4 A n z_0^n I}{\nu W^2}\right)^{-1/n} \qquad \text{(Eq. 1)}$$

Where z = outgoing moisture ratio [kg $H_2 0$/kg d.p.]
z_0 = ingoing moisture ratio [kg $H_2 0$/kg d.p.]
I = press impulse = press load/speed [(kN/m)/(m/s)]
n = compressibility factor
A = specific permeability [g/m]
W = basis weight [kg/m^2]
ν = kinematic viscosity of water [m^2/s].

McDonald and Amini recommend determining the model parameters, compressibility factor and the specific permeability, by pressing handsheets in a laboratory press [12]. Unfortunately, we were not able to do this. Instead some old measurements were fit to obtain the parameters and the result was evaluated qualitatively.

Drying Section
The drying section of the base board production was modeled including the steam and condensate system. The number of the steam heated cylinders in the model is 75. Steam headers bringing the steam from the power plant start the model in the steam side and the condensate return flow to the power plant forms the other model boundary. The piping network of the steam and condensate system was modeled using the homogeneous two-phase flow model of the simulation platform. The drying cylinder and free draw models previously reported by Niemenmaa [13] were used and partially further developed in this study. The main calculation principles of the drying model are presented here. Figure 1 presents a view from pictures of the 2nd steam group.

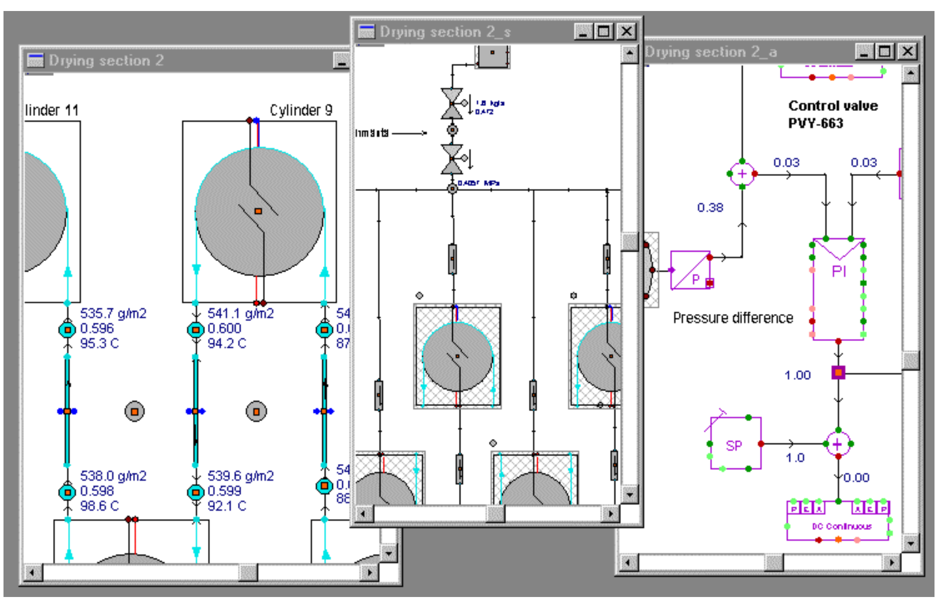

Figure 1. The graphical specification of the model for each steam group is divided into three pictures: the web side, the steam and condensate system and the related controls.

Heat transfer in cylinders.

The heat transfer coefficient from steam inside the cylinder through the condensate layer to the inner surface of the cylinder is calculated using the theoretical expression by Appel and Hong [14]. The modeled drying section consists also cylinders with turbulence bars, and in those cases a constant coefficient has been used instead. The cylinder shell is radially discretized into three parts. The one-dimensional heat conduction model is used in calculation of heat flow through the cylinder wall. Also, the heat capacity of the cylinder heads has been considered. An example of a drying section profile for cylinder inside steam, inner surface, outer surface and web temperatures after each cylinder, and web moisture content can be seen in Figure 2.

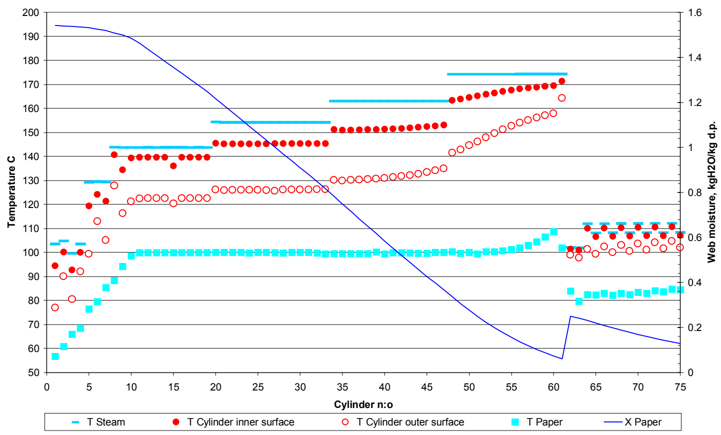

Figure 2. An instantaneous profile from the drying section model. Temperatures (°C) of the cylinder inside steam and inner and outer surfaces, as well as web temperature and moisture content (kg H_2O/kg d.p.) after each cylinder are presented as a function of cylinder number.

Evaporation from paper.
The following approximation of the Stefan equation expresses the evaporation rate $\dot{m}_{ev}/A$ from paper to air [15]:

$$\frac{\dot{m}_{ev}}{A} = \alpha \cdot C \cdot \ln\left(\frac{p_{tot} - p_{va}}{p_{tot} - p_{vp}}\right) \qquad \text{(Eq.2)}$$

Where α = paper-to-air heat transfer coefficient
p_{tot} = air total pressure
p_{vp} = vapor partial pressure on paper surface
p_{va} = vapor partial pressure in surrounding air
C = constant

Differences in felting are taken into account by the paper-to-air heat transfer coefficient. Below the critical moisture content, the evaporation front has moved inside the paper surface. The evaporation reduction is obtained by using sorption isotherms:

$$p_{vp} = \varphi(T_p, z) \cdot p_0 \qquad \text{(Eq.3)}$$

Where $\varphi(T_p,z)$ = sorption isotherm of paper
T_p = paper temperature
z = paper moisture ratio
p_0 = vapor partial pressure for free water

For wet paper the function $\varphi(T_p,z) = 1$. In the hygroscopic region, where the paper moisture is less than the critical moisture content, the function $\varphi(T_p,z) < 1$, and approaches zero as paper moisture decreases. Sorption isotherms for various paper grades can be found in literature [16]. Vapor partial pressure for free water is calculated using Antoine’s equation and the vapour partial pressure in air is solved using the given air humidity and air total pressure in dryer pockets. Air humidity and pressure are assumed to be constants during GC's. The incremental change in the paper moisture content can be solved from mass balance when the initial moisture content and the evaporation rate $\dot{m}_{ev}/A$ are known.

The heat and mass transfer between outer cylinder surface, paper and air in the hood are solved explicitly by the cylinder and free draw models, and are added as source terms into the continuity equations of the steam and condensate system. The calculation of the heat and mass transfer of the cylinder-web-air is discretized into several steps, as well as calculation in the free draws. The number of partitions is given by user, being 20 in this study.

A single layer web model is used. So the state of the web in each position in the machine direction is described by average temperature and moisture. In practice, there are gradients in paper thickness direction in moisture and temperature. The thickness depending resistance for the heat and mass transfer is approximated in the model by a same kind of evaporation reduction factor that has been used to model evaporation through a pigment coating [15].

Control System

The control system was modeled in parallel with the process modeling. The number of control loops in the model is 74.

The functionality of the AGC program was modeled in detail using the basic automation components of the simulation platform. Thus the AGC model calculates the target values for the new grade, and handles the GC operations also in the situation, that the parameter values are changed from the mill values. Figure 3 shows the user interface of the AGC in the simulator graphics.

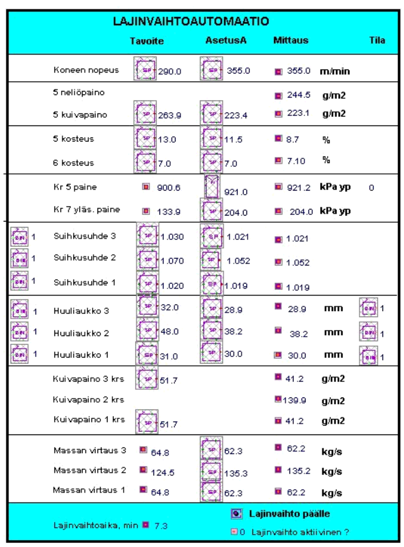

Figure 3. The AGC display in the simulator graphics resembles the main picture of the AGC package in the mill DCS. Values in the three main columns are targets for the new grade, current setpoints and measurements.

MODEL VALIDATION

When a simulator is used in what-if studies, its most important characteristics are model fidelity and that the users know the model limitations. The focus of the simulation study was on finding better values for those AGC parameters that define the mutual coordination and rates of the ramps. To be able to do that, the simulator must confidently predict the effects of the simultaneous ramps of the various operating variables on the critical variables like moisture and basis weight. In addition, the model of the AGC must function like the real one to enable what-if studies with new parameter settings. The parameters that we focused on are equal for the whole operating area, so the new values must suit well for changes between all produced grades. Accordingly, the simulator validity must cover the whole operating area of the machine. This is a major motivation for using a mechanistic modeling approach in this kind of study instead of identification of linear black-box models.

Main emphasis in validation runs was naturally placed on dynamics during GC's. GC's produce good data for model development and validation in general, because of the big transients in such many variables [17]. A large amount of validation data can be collected easily without any additional experimentation. At this mill, the DCS collects automatically a large data set from every GC. In fact, in this project we did not make any machine bump tests, or additional measurements because of the modeling and validation.

Most of the time spent in validation went into tuning of the drying section model. Besides the measurements taken by the DCS, we had an opportunity to use a report of a recent study where temperature measurements of paper, cylinder surface and dryer pockets (moisture as well) were taken in the drying section by hand. Simulated drying section profiles like shown in Figure 2, showed good agreement with these measurements. Additionally, it would have been very interesting to see how the simulated moisture and temperature profiles reflect reality in dynamic situation. The model of the steam and condensate system needed quite a lot of attention as well because of the noticeable amount of details measured, and thus verified.

Another time consuming task was to get the AGC model to perform GC's in the simulator just like the actual AGC does on the machine. We found differences that occasionally appeared between simulations and mill data. We figured out that the differences come from the fact that some operators were using the AGC in a slightly different way than we did in the simulations. By using the simulated GC's as reference we could sieve out such type of actions in using the AGC that were undesirable when aiming at best result. For example, one of these issues was the calculation of the new target values: some operators let the AGC calculate them far too early. The best way is to use the mode of automatic target updating. Then the final calculation is done just before the GC is initiated. Therefore, we came across to this kind of small separate issues, established practice in using different options and modes in a wrong way. This is quite natural when a long time has passed since the system was taken into use and users trained. But consequently, in all those cases the GC's were not as good as they could have been with the tuning of that time. After these faults were identified, the operators were advised to the optimal and consistent use of the AGC.

Simulation Example

Figure 4 presents an example of a GC, which is selected from the historical data and then repeated with the simulator. Measured values are drawn with black, and gray curves show the corresponding simulation. Time scale is presented in seconds and total time is 25 minutes. Speed (see picture up left) has been changed from 355 to 290 m/min. Thick stock flows of top and bottom layers have practically same values (picture up right). The absolute change in the steam pressure is rather small in this case. The moisture and basis weight controls are switched on at time 600 s. In this GC also the slice opening controls have been included in the AGC (picture middle right). The three jet-wire ratios have been ramped to new values, as well, though not seen in the figure.

Overall, the simulation model showed very good agreement with the measurements. Like noticed in many of the previous GC studies, we found out as well, that the biggest challenge in modeling is to capture the moisture dynamics accurately. One problem was to get the moisture correspond to the measurement before each GC. The only workable solution was fine-tuning of the drying model for each GC case. Without accurate models explaining the effect of refining and furnish type, this kind of tuning is needed. The tuning is done automatically when the model state (machine speed, thick stock flows, wet press loads, etc.) is simulated to correspond the old grade situation. Still, the following three problematic phenomena could be identified concerning the model accuracy:

- After a large moisture excursion, the simulated moisture returns to the normal level earlier than the measurement. This can also be seen in the bottom right picture of the Figure 4. Cylinder surface and hood air measurements during GC's would help to analyze if the difference comes form the drying section model. The key reason can be in the modeling of wire or press section as well.
- Another feature that was noticed relates to the amplitude of simulated moisture peaks. The peaks have often been smaller than the measured ones. An example of this kind of case is shown in Figure 5. Anyhow, the form of the dynamic behavior fits well to the measurements.

- Furthermore, in Figure 4 it can be seen that the final moisture level does not exactly equal with the measured one. So, even if the initial moisture was tuned to fit the measurements, this happened from time to time. It seemed to be very difficult to tune the model so, that the final moisture never differs from the measured level.

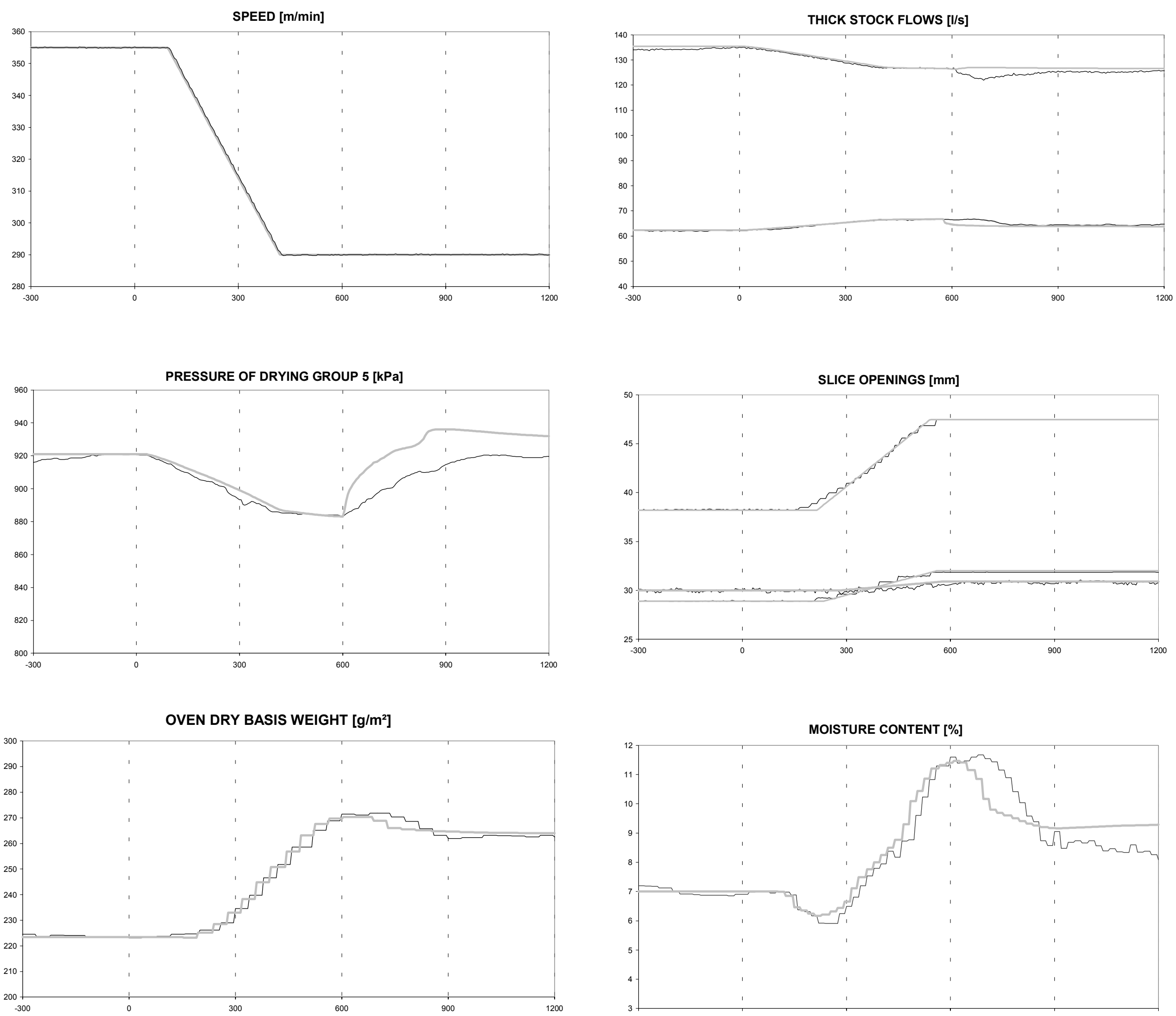

Figure 4. Measured (black) and simulated (gray) variables in a GC: machine speed, thick stock flows of three layers, slice opening of three headboxes, steam pressure in 5th steam group, oven dry basis weight and moisture content before the size press. Time scale is in seconds.

UTILIZATION

After confidence was gained that the simulator can consistently repeat the GC's that have been made in the real machine, the what-if experiments were started. The above-mentioned inaccuracy in moisture dynamics did not hinder us from studying effects of various tuning parameters of the AGC.

Whenever a new GC was taken for further studies, we used the following procedure:

- Select an interesting GC for a base line data (e.g. the one that has just been done today on the machine!).
- Open the data into spreadsheet. The target file has been configured so that the setpoints that define the state before the GC, and the new grade targets that are not calculated by the AGC, are automatically picked up.
- Run the model state to correspond the old grade in the selected base line data. This is most easily done with a script file. At the same simulation run the drying part is automatically fine-tuned so, that the sheet moisture

content before the grade change is exactly correct (otherwise the calculated new targets for the steam pressures would not be the same as in the historical data).

- Simulate the GC. This is usually done as a batch run, although the simulation speed is about 4 times the real time (600 MHz PC). The simulator writes values of pre-defined variables into a file.
- Compare the simulated data with the historical data. The former mentioned spreadsheet file is used here as a ready configured template for the comparison.

After this procedure, if the result seems reasonable, ideas, whether old or new ones, can be tested using this new GC as a reference for the performance. It is easy to design a series of simulation batch runs with different parameter values and check what happens to the performance.

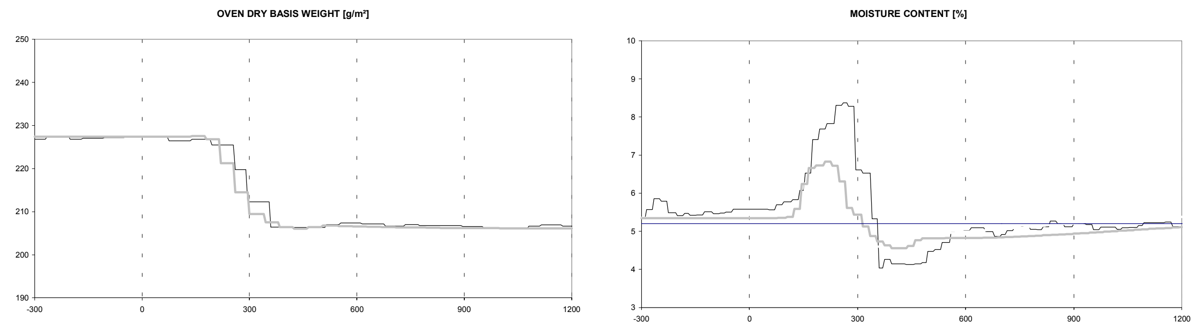

Figure 5. Measured (black) and simulated (gray) variables in another GC: oven dry basis weight, and moisture content. The AGC parameters that define the ramping rates have been changed from the case in Figure 4.

First simulations concentrated on speeding up the GC's simply by increasing the ramping rates of those variables, which most often limited the total ramping time. One by one higher rates were tried out and the effects on the performance analyzed. The positive impact on GC time was very clear from the basis weight point of view. The moisture fluctuations seemed to get somewhat worse in the amplitude, but on the other hand, they settled down faster. Still, the simulated maximum and minimum moisture values were not too big to cause web breaks, so we were encouraged to tune the actual AGC's ramping rates faster as well. For example, originally the ramping rate of the machine speed was 8 m/min^2. The rate was increased in three steps. In the GC shown in Figure 4, the rate is 12 m/min^2, and in Figure 5, it is 20 m/min^2. In the GC of Figure 5, the other variables were included in the AGC just like in the case of Figure 4. No change in the accuracy of the simulator was noticed when the measurements from the GC's with higher ramping rates were compared against corresponding simulations.

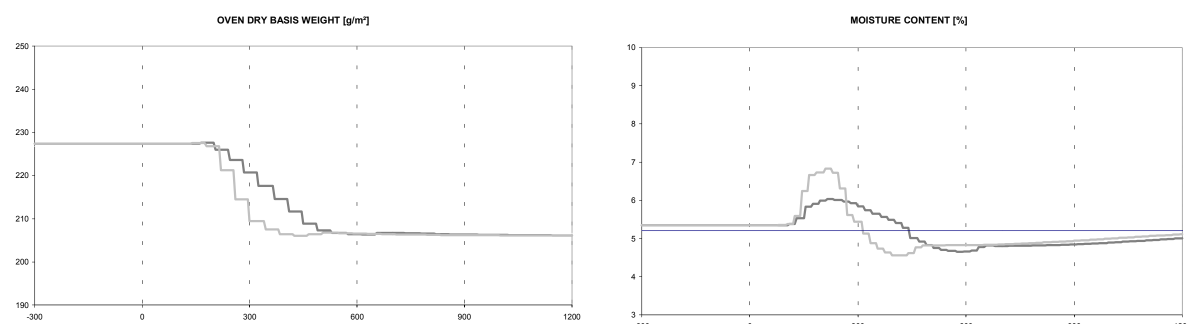

Figure 6. Simulated values in the same GC as in Figure 5. Light gray curves are the same as in Figure 5. Dark gray curves correspond oven dry basis weight and moisture in the case that no changes would have been made to the AGC parameters.

Figure 6 shows the same GC as in Figure 5, but with simulated results only. The light gray curve is the same as in Figure 5. The dark gray curve shows the same GC using the original AGC parameters (e.g. machine speed ramping rate 8 m/min^2). It can be clearly seen, that because of the faster ramping the basis weight reaches the target value earlier, and also the moisture fluctuation is squeezed into a smaller time window.

The trials with different AGC parameters continue at the mill. Now the focus is to find better mutual timing for the ramps in order to decrease the moisture fluctuations during the GC's. For example, changes to start delays of steam pressure and thick stock flow ramps are studied. When good candidates for the parameters are found, the performance is tested with a large group of GC's to cover the whole area of operation. At the mill, statistics concerning every GC before and after the first parameter changes, have been collected. Thus quantitative information is gained for later evaluation of each step taken in the AGC tuning.

FUTURE WORK

The model development continues. The scope of the model will not be extended but ways to increase the accuracy especially concerning the moisture dynamics are sought for. To achieve more accuracy we probably have to make extra measurements on wire, press and drying sections, and bump tests with the machine must, as well, be considered.

The developed model offers a platform for troubleshooting, related to GC's or other issues on the simulator's scope. What comes to development of GC's, with the existing tool it can be quickly checked if a new idea, e.g. presented in literature, is worth of further studies. The model usage for operator training and support has also been discussed.

Another project where the model will be used aims at increasing the drying capacity of the machine. Effects of additional dryers, like air impingement drying units, into the production capacity are studied. The influence into the moisture dynamics in GC's, will be covered as well. The model development of air impingement drying has been reported recently [18].

CONCLUSIONS

The 3-ply paperboard production process was modeled from the pulp chests to the drying of base board. The model was verified with tens of grade change runs that were selected from the mill historical data. Modeling and validation phase helped us to understand the interactions during grade changes. Additionally, we were able to spot some weaknesses in operational practices concerning the use of the AGC program.

For a multi-ply process, it is a demanding task to figure out how the AGC parameters should be changed to speed up grade changes and simultaneously remove unwanted moisture fluctuation. The simulator helped to cut the problem into pieces, and offered a way to visualize the problem and compare the solution candidates. A procedure was developed to simulate grade changes and hunt for better AGC parameter values. It is no more necessary to only rely on intuition in the tuning. The first parameter changes have been carried out to the real AGC with good results. Besides the ongoing grade change development, also new applications for the model have been found.

References

1. Miyanishi, T., Iida, K. and Iwatsu T., "Dynamic simulation for efficient paper machine grade change", TAPPI Journal, January 1988, pp. 49-56.

2. Ihalainen, R. and Ritala, R., "Optimal grade changes", Proceedings of Control Systems '96, April 30. - May 2., 1996, Halifax, Nova Scotia, Canada, pp. 213-216.

3. Murphy, T.F., Chen, S.C., "Fast grade change for paper-making processes", Proceedings of Control Systems 2000, May 1-4, 2000, Victoria, British Columbia, pp. 189-192.

4. Murphy, T.F., Palumbo, R. and Chen, S.C., "Reducing production loss from paper grade change", TAPPI 2000 Process Control, Electrical and Information Conf., Williamsburg, VA, March 26.-30., 2000, pp. 175-181.

5. Mori, Y., Shimizu, H. and Takao, K., "Development of a new automatic grade change control system for paper machine", Proceedings of Control Systems 2000, May 1-4, 2000, Victoria, British Columbia, pp. 231-234.

6. Viitamäki, P., "Hybrid modeling of moisture in paper machine grade changes", Proceedings of Control Systems 2000, May 1-4, 2000, Victoria, British Columbia, pp. 239-242.

7. Bale, S., Nuyan, S., Spring, R., Taha, O. and Dumont, R., "Automatic grade change and optimisation at Frasier Papers' Madawaska operations", 86th annual meeting of PAPTAC, February 1.-3., 2000, pp. B203-B207.

8. Välisuo, H., Niemenmaa, A., Lappalainen, J., Laukkanen, I. and Juslin, K., "Dynamic simulation of paper and board mills: a case study of an advanced grade change method", TAPPI Engineering Conference 1996, September 16-19, Chicago, pp. 491-498.

9. Kuusisto, R., Kosonen, M., Shakespeare, J. and Huhtelin, T., "Multivariable control of paper machine grade changes", 87th annual meeting of PAPTAC, February 1, 2001, pp. C141-144.

10. Airikka, P., Kokko, T., Lautala, P. and Huhtelin, T., "Simulation of paper machine basis weight and ash content dynamics", Proceedings of the IASTED International Conference Applied Modelling and Simulation, September 1.-3., 1999, Cairns, Australia, 6p.

11. Silvennoinen, E., Juslin, K., Hänninen, M., Tiihonen, O., Kurki, J., Porkholm, K., "The APROS Software for Process Simulation and Model Development", Technical Research Centre of Finland, Research reports 618, 1989, Espoo, Finland.

12. McDonald, D. and Amini, J., "Predicting the press dewatering of heavyweight grades", TAPPI Journal, VOL 83 (2), 2000, pp. 79-82.

13. Niemenmaa, A., Lappalainen, J., Laukkanen, I. and Juslin, K., "Dynamic modelling and simulation of paper machine drying section", Proceedings of the 10th International Drying Symposium (IDS'96), Krakow, Poland, July 30. – August 2., 1996, pp. 1157-1164.

14. Appel, D. and Hong, S., "Optimizing heat transfer using bars in dryers", International Water Removal Symposium, London, 1975.

15. Heikkilä, P., "A study on the drying process of coated paper webs", Ph.D. Thesis, Åbo Akademi, 1993, Turku, Finland, 150 p.

16. Paltakari, J., "Koelaite ja menetelmä paperin kuivatusteknisten parametrien määrittämiseksi", Lic. Tech. Thesis, Helsinki University of Technology, 1995, Helsinki, Finland (in finnish).

17. Menani, S., Koivo, H.N., Huhtelin, T. and Kuusisto, R., Dynamic modeling of paper machine from grade change data, proceedings from Control Systems '98, Porvoo, Finland, September 1.-3., 1998, pp. 79-86.

18. Tuuri, S., Heikkilä, P. and Hamström, K., Dynamic model of drying section including air impingement unit, 3rd EcoPaperTech Conference, June 4.-8., 2001, Helsinki, Finland, 11p.